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METHOD AND APPARATUS FOR CALIBRATING COMMUNICATIONS CHANNELS

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METHOD AND APPARATUS FOR CALIBRATING COMMUNICATIONS CHANNELS

BACKGROUND

[0001] Many different types of transmission lines exist and are used for a variety of purposes. For example, transmission lines are often used as the media that carries data over long distances, medium distances, and short distances. A transmission line may be anything from a coaxial cable carrying data signals over long distances to an almost microscopic metal trace that carries signals within tiny integrated circuits. As is known, a signal driven onto one end of a transmission line reflects off of the other end of the transmission line unless the other end of the transmission line is terminated with an impedance that matches the characteristic impedance of the transmission line. As is also known, driving a periodic signal onto a transmission line may cause voltage and/or current wave patterns with distinct characteristics to be induced on the transmission line. For example, a periodic signal whose frequency corresponds to a quarter wave or a half wave of the length of a transmission will typically generate a resonate standing wave on the transmission line if the transmission line is terminated in an open circuit or a short circuit.

[0002] Under certain circumstances, it may be advantageous to determine the length of, propagation delay through, or other characteristic of a transmission line. As just one (non-limiting) example, there are circumstances in which it would be advantageous to adjusts the propagation delay through a plurality of transmission lines so that signals driven through the transmission lines arrive at their destinations at the same time or within a specified tolerance. For this and other applications, it would be advantageous to utilize wave reflection properties of a transmission line to determine one or more characteristics of the transmission line.

BRIEF SUMMARY

[0003] In an exemplary embodiment of the invention, a periodic signal is driven onto a transmission line, and the frequency of the periodic signal is varied. The initial frequency of the periodic signal may be selected to correspond to a quarter wave or half wave of an estimated length of the transmission line. A null or a peak in the envelope of the voltage or current wave induced on the transmission line by the periodic signal is detected at or near the end of the transmission line onto which the signal is driven. The frequency of the periodic signal that

caused the null or peak may be used to calculate the length of the transmission line or a propagation delay through the transmission line. A plurality of transmission lines may be deskewed by determining the propagation delay through each transmission line and adjusting a variable delay in each transmission line so that the transmissions lines have approximately equal overall propagation delays.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] Figure 1 is a simplified block diagram of a system that may be used to determine the length or propagation delay of transmission line 112.

[0005] Figure 2 shows a standing wave that may be induced on the transmission line 112 of Figure 1.

[0006] Figure 3 illustrates an exemplary process for determining the length or propagation delay of transmission line 112 of Figure 1.

[0007] Figures 4a, 4b, 5a, and 5b illustrate exemplary envelope wave patterns generated by the envelope detector 122 of Figure 1.

[0008] Figure 6 is a simplified block diagram of another system that may be used to determine the length or propagation delay of transmission line 112

[0009] Figure 7 is a simplified block diagram of the analyzer 602 of Figure 6.

[0010] Figure 8 illustrates exemplary operation of the processor 710 of Figure 7.

[0011] Figure 9 shows a simplified block diagram of a system for testing electronic devices.

[0012] Figure 10 is a simplified block diagram of a configuration that may be used to deskew a plurality of communications channels.

[0013] Figure 11 illustrates exemplary operation of the automatic calibration module 1022 of Figure 10.

[0014] Figure 12 illustrates an exemplary process for determining the value of an unknown impedance.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

[0015] This specification describes exemplary embodiments and applications of the invention. The invention, however, is not limited to these exemplary embodiments and applications or to the manner in which the exemplary embodiments and applications operate or are described herein.

[0016] Figure 1 illustrates a simplified block diagram of an exemplary system for determining the length and/or propagation delay through a transmission line 112. Although schematically shown as a coaxial cable in Figure 1, transmission line 112 may be any type of transmission line, including without limitation a coaxial cable, a twisted pair, a strip line, a microstrip, a trace, etc. Indeed, transmission line 112 may comprise a combination of any of the foregoing and may further include vias, switches, electronics etc. The transmission line 112 shown in Figure 1 includes a signal line 120 that carries the signal current and a return line 114, which may connected to ground 116 as shown in Figure 1. A proximal end 110 of the transmission line is connected to the output 108 of a driver 106. The distal end 118 of transmission line 112 may be left open or, the transmission line may alternatively be shorted by connecting the distal end 118 to ground 124. A signal generator 102 generates a periodic signal that is input 104 into driver 106, which drives the periodic signal onto transmission line 112. Transmission line 112 has a length "L," and the input 126 of an envelope detector 122 is connected to the transmission line 112 along its length "L" at or near its proximal end 110. A non-limiting example of an envelope detector is a circuit for demodulating an amplitude modulated (AM) signal. The input 126 of the envelope detector 122 may be AC coupled (e.g., through a capacitor) to the transmission line 112.

[0017] As is known, a signal driven by driver 106 onto the proximal end 110 of the transmission line 112 propagates down the transmission line and reflects off of the distal end 118 back up the transmission line. A periodic signal driven by driver 106 onto transmission line 112 may result in a voltage wave pattern on transmission line 112. Figure 2 illustrates such a standing wave 200. As shown, Figure 2 shows a standing voltage wave 200 in which the horizontal axis 216 represents position along the length of transmission line 112, and the vertical axis 214 represents the voltage difference between the signal line 120 and the return line 114 of transmission line 112. In Figure 2, the vertical axis 214 represents the proximal end 110 of the transmission line

112, which is where the input 126 of envelope detector 122 is connected to transmission line 112.

[0018] As shown in Figure 2, the envelope 201 of such a wave pattern may be periodic and may include voltages peaks (e.g., 202, 206, and 210) and nulls (e.g., 204, 208, and 212). As is known, if the periodic signal driven onto the transmission line 112 has a wavelength that is a quarter of the length "L" of the transmission line 112 or is a multiple of a quarter of the length "L," a peak (e.g., 202, 206, 210) or a null (e.g., 204, 208, 212) of the voltage envelope 201 occurs at the proximal end 110 of the transmission line 112. The same is true if the periodic signal that has a wavelength that is a half or a multiple of a half of the length "L" of transmission line 112. For both a quarter wave signal (e.g., a signal with a wavelength that is one fourth or a multiple of one fourth of the length "L") and a half wave signal (e.g., a signal with a wavelength that is one half or a multiple of one half of the length "L" of transmission line 112), whether a peak (e.g., 202) or a null (e.g., 204) occurs at the proximal end 110 (represented in Figure 2 by axis 214) of transmission line 112 depends on whether the distal end 118 of transmission line 112 is open or shorted.

[0019] More specifically, if the distal end 118 of transmission line 112 is open and the signal driven onto the proximal end 110 of the transmission line has a quarter wavelength, then a null (e.g., 204) occurs at the proximal end 110 of transmission line 112. If the distal end 118 of transmission line 112 remains open but the signal driven onto the proximal end 110 of the transmission line has a half wavelength, then a peak (e.g., 202) occurs at the proximal end 110 of transmission line 112. On the other hand, if the distal end 118 of transmission line 112 is closed (shorted) and the signal driven onto the proximal end 110 of the transmission line has a quarter wavelength, then a peak (e.g., 202) occurs at the proximal end 110 of transmission line 112. If the distal end 118 of transmission line 112 remains closed (shorted) but the signal driven onto the proximal end 110 of the transmission line has a half wavelength, then a null (e.g., 204) occurs at the proximal end 110 of transmission line 112. Table I below summarizes the foregoing:

Table I

Distal End	Wavelength	Voltage At Proximal End
Open	quarter	Null
Open	half	Peak
Shorted	quarter	Peak
Shorted	half	Null

[0020] As will be seen, signal generator 102 generates a periodic signal that driver 106 drives onto transmission line 112. The frequency of the signal generated by signal generator 102 is changed until the output 128 of the envelope detector 122, whose input 126 is connected at or near the distal end 110 of the transmission line 112, indicates a null or peak, which, as discussed above, indicates that the signal driven onto the transmission line 112 is a quarter wave or half wave signal (with respect to the length "L" of the transmission line). (How near the input 126 of envelope detector 122 should be connected to the proximal end 110 of the transmission line 112 depends on the precision desired or needed in determining the actual length of the transmission line 112 or the propagation delay through the transmission line.) Knowing the frequency of the signal and whether the driving signal is a quarter wave or a half wave signal, one can determine both the length "L" of the transmission line 112 and the propagation delay of a signal through the transmission line. This is because one can calculate the wavelength of the signal from the frequency of the signal, and one can calculate both the length "L" of and the propagation delay through the transmission line 112 from the wavelength.

[0021] As is known, the wavelength (λ) of a periodic electromagnetic signal propagating down a transmission line is equal to the frequency (f) of the signal multiplied by the propagation velocity (v_p) of the signal, which is equal to the speed of light in free space ("c") divided by the square root of the relative permeability ("e_r") of the dielectric material (not shown) between the signal line 120 and the return line 114 of the transmission line 112. Mathematical formulas for the foregoing are as follows: $\lambda = v_p \div f$, and $v_p = c \div \sqrt{e_r}$ (where $\sqrt{e_r}$ represents the square root of e_r). For a quarter wave signal, the length "L" of the transmission line 112 is one fourth the full wavelength ($L = \lambda \div 4$). Similarly, for a half wave signal, the length "L" is half the full wavelength ($L = \lambda \div 2$). The propagation delay through the transmission line is one fourth the inverse of the frequency ($D = 1 \div (4 * f)$) for a quarter wave signal, and one half the inverse of the frequency ($D = 1 \div (2 * f)$) for a half wave signal (where D is propagation delay).

[0022] Figure 3 illustrates exemplary operation of the system of Figure 1. At step 302, the distal end 118 of transmission line 112 is configured to be either open or shorted. As discussed above, the distal end 118 is left open by not connecting the signal line 120 to a conductive element; the distal end 118 is shorted by connecting the signal line 120 to ground 124 (assuming that the return line 114 is connected to ground as shown in Figure 1). At step 304, an initial frequency setting for signal generator 102 is selected. There are any number of ways to select an

initial frequency. For example, the initial frequency may be selected to correspond to a quarter wavelength or half wavelength of an estimated length "L" of the transmission line 112. Manipulating the equations discussed above, frequencies corresponding to a quarter wavelength and a half wavelength of the estimated length "L" of the transmission line 112 may be calculated as follows:

for quarter wavelength: $f_o = c \div (4 * L_{est} * \sqrt{e_r})$

for half wavelength: $f_o = c \div (2 * L_{est} * \sqrt{e_r})$

where:

- * indicates multiplication
- f_o is frequency
- L_{est} is the estimated length of the transmission line 112
- $\sqrt{e_r}$ is the square root of the relative permeability ("e_r") of the dielectric material (not shown) between the signal line 120 and the return line 114 of the transmission line 112
- c is the speed of light through free space (which is approximately 3 x 10^8 meters/second). (Of course, using a more precise number for the speed of light will result in a more precise calculation.)

Example: The following example shows use of the foregoing formulas to calculate an initial frequency at step 304 of Figure 3 using the foregoing formulas. In this example, it is assumed that $\sqrt{e_r}$ is 2 and the estimated length (L_{est}) of the transmission line is 15 centimeters.

- An initial frequency for a quarter wave signal would be as follows: $f_o = 3x10^8 \div (4 * 0.15 * 2)$, which equals 250 megahertz.
- An initial frequency for a half wave signal would be as follows: $f_o = 3x10^8 \div (2 * 0.15 * 2)$, which equals 500 megahertz.

[0023] At step 306, signal generator 102 generates a periodic signal that is input 104 to driver 106, which drives the signal onto transmission line 112. The periodic signal may be any shape. For example, signal generator 102 may generate a sinusoidal, periodic signal that is input 104 into driver 106. As another example, signal generator 102 may include an internal filter (not shown) that passes to the input 104 of driver 106 only the fundamental wave, a particular

harmonic wave, or a combination of the fundamental wave and a particular harmonic wave or particular harmonic waves so that only such a wave or combination of waves are driven onto the transmission line 112. Of course, such a filter or filters could be placed outside of the signal generator 102, such as between the signal generator 102 and the driver 106 or at the output 108 of the driver. Regardless of the filtering and shape of the signal, the frequency of the signal driven onto transmission line 112 should be the frequency selected at step 304.

[0024] As discussed above, driving the signal onto the transmission line 112 will cause a standing wave that may look generally like wave 200 in Figure 2 to appear on transmission line 112. As also discussed above, the standing wave 200 in Figure 2 does not correspond to a quarter wave or half wave signal with respect to the length "L" of transmission line 112 because neither a null nor a peak appears at axis 214, which, as mentioned above, corresponds to the point along the transmission line 112 where input 126 to envelope detector 122 is connected to the transmission line, which, as shown in Figure 1, is preferably at or near the proximal end 110 of the transmission line 112. To find the signal whose frequency creates a null or peak at the proximal end 110 of the transmission line 112, the signal generator 102 is caused at step 306 to sweep the signal input 104 into driver 106 and driven onto the transmission line 112 through a range of frequencies starting with the initial frequency selected at step 304. The signal generator 102 may sweep the signal continuously and smoothly over the range, or the signal generator 102 may step the signal from one discrete frequency to another through the range. Preferably, the frequency range is selected to include a range of frequencies that correspond at least to a ¼ wave or a ½ wave of the initial frequency selected at step 304.

[0025] As the signal generator 102 sweeps the frequency range, envelope detector 122 receives at its input 126 the standing wave (e.g., like wave 200 shown in Figure 2) and outputs 128 the envelope (e.g., like the envelope 201 shown in Figure 2) of that standing wave as the standing wave varies with the change in the frequency of the signal driven onto the transmission line 112. Figure 4a illustrates a plot of the output 128 of envelope detector 122 where the sweep through the frequency range is continuous and smooth, and Figure 4b illustrates a plot of the output 128 where the sweep through the frequency range steps from one discrete frequency to another. The frequency sweep in both Figure 4a and 4b are from the initial frequency f_0 selected at step 304 through f_{45}. (In both Figures 4a and 4b, the horizontal axis 416 represents the frequency of the signal driven onto transmission line 112, and the vertical axis 414 represents the voltage

appearing at the output 128 of the envelop detector 122.) As mentioned above, a frequency that corresponds to a peak or null in Figure 4a or Figure 4b is a quarter wave or half wave signal with respect to the length "L" of the transmission line 112.

[0026] While sweeping the frequency of the signal driven onto transmission line 112 at step 306, the process of Figure 3 looks at step 308 for a peak (e.g., 402a, 406a, 410a in Figure 4a or 402b, 406b, 410b in Figure 4b) or a null (e.g., 404a, 408a, 412a in Figure 4a or 404b, 408b, 412b in Figure 4b) in the envelope wave form (e.g., 128a in Figure 4a or 128b in Figure 4b) generated at the output 128 of envelope detector 122. It should be noted that steps 304 and 306 may occur concurrently or sequentially. Indeed, steps 304 and 306 may occur in part sequentially and in part concurrently, that is, execution of those steps may overlap.

[0027] Per table I above, one looks for a null or a peak at step 308 depending on whether the distal end 118 of the transmission line 112 was left open or shorted at step 302 and whether the initial frequency f_0 selected at step 304 was selected based on a quarter wave or a half wave of the estimated length "L" of the transmission line. That is, if the distal end 118 of the transmission line 112 is left open at step 302, then: one looks for a null at step 308 if the initial frequency selected at step 304 was based on a quarter wave of the estimated length of the transmission line 112; or one looks for a peak at step 308 if the initial frequency selected at step 304 was based on a half wave. On the other hand, if the distal end 118 of the transmission line 112 is shorted at step 302, then: one looks for a peak at step 308 if the initial frequency selected at step 304 was based on a quarter wave of the estimated length of the transmission line 112; or one looks for a null at step 308 if the initial frequency selected at step 304 was based on a half wave. Table II below summarizes the foregoing.

Table II

Step 302	**Step 304**	**Step 308**
Distal end 118 open	Initial frequency based on quarter wave	Look for null
Distal end 118 open	Initial frequency based on half wave	Look for peak
Distal end 118 shorted	Initial frequency based on quarter wave	Look for peak
Distal end 118 shorted	Initial frequency based on half wave	Look for null

[0028] There are any number of ways to detect a peak or a null in the envelope waveforms 128a or 128b. Indeed, detecting a peak or null may be as simple as a user monitoring the displayed output of the envelope detector 122 until he or she visually sees a null or peak. (The user may also manually adjust the frequency of the signal driven onto the transmission line while looking at the displayed output of the envelope detector 122.) Figures 4a and 4b illustrate another exemplary way to detect a peak or a null, and Figures 5a and 5b illustrate yet another exemplary way.

[0029] The method illustrated in Figures 4a and 4b monitors the rate of change of the envelope (e.g., 128a in Figure 4a or 128b in Figure 4b). A peak occurs where the rate of change of the envelope goes from positive to negative. That is, where the envelope signal changes from increasing in value to decreasing in value, there is a peak. Conversely, where the rate of change of the envelope goes from negative to positive, there is a null. An example is shown in Figure 4b. As shown in Figure 4b, the envelope 128b increases in value from frequency f_0 through f_5. The change from f_5 to f_6, however, causes the envelope 128b to decease in value. Thus, one can determine that a peak 402b occurs at one of f_5 or f_6 or between f_5 and f_6. It can thus determined at step 308 in Figure 3 that a peak occurs at f_5, f_6 , or at a frequency between f_5 and f_6 (e.g., an average of f_5 and f_6). Of course, the smaller the increments between frequency steps in Figure 4b, the greater the accuracy. Peak 402a in Figure 4a may be similarly detected. For example, the slope of the envelope 128a may be analyzed to determine whether the envelope is increasing or decreasing in value at a particular frequency.

[0030] In like manner, a null may be detected by looking for a change from decreasing values of the envelope 128b to increasing values. For example, in Figure 4b, every change in frequency from f_6 or f_{12} results in a decrease in the envelope 128b. The change from f_{12} or f_{13}, however, causes the envelope 128b to increase. It can thus determined at step 408 in Figure 3 that a null occurs at f_{12}, f_{13} , or at a frequency between f_{12} and f_{13} (e.g., an average of f_{12} and f_{13}). Again, the smaller the increments between frequency steps in Figure 4b, the greater the accuracy. Null 404a in Figure 4a may be similarly detected (e.g., by examining the slope of the envelope to determine whether the envelope is increasing or decreasing at a particular frequency).

[0031] Like the method illustrated in Figures 4a and 4b, the method illustrated in Figures 5a and 5b also monitors the rate of change of the envelope (e.g., 128a in Figure 5a or 128b in Figure 5b). To find a peak or a null, the method illustrated in Figures 5a and 5b looks for a particular

voltage level on the envelope signal output 128 by envelope detector 122. The method finds a pair of equal voltages (or equal within a specified tolerance) along the envelope. If the first voltage occurs while the envelope signal is increasing in value, then the average of the frequencies at the voltages in the pair corresponds to a peak. If, on the other hand, the first voltage occurs while the envelope signal is decreasing in value, then the average of the frequencies at the voltages in the pair corresponds to a null.

[0032] The foregoing is illustrated in both Figure 5a and Figure 5b. In Figure 5a, voltage 502a is selected as the target voltage, and as can be seen, points 504a, 506a, and 508a represent points on envelope 128a that equal the target voltage 502a. As can be seen, voltage level 502a is detected on the envelope 128a while the signal driven onto the transmission line 112 has a frequency f_{10}, f_{15}, and f_{24}. It can thus be determined that a peak or null occurs between both the frequency pair f_{10} and f_{15} and the frequency pair f_{15} and f_{24}. Indeed, the peak or null occurs at the average of the frequencies in each pair. That is, a peak or null occurs at frequency $f_{12.5}$ (the average of f_{10} and f_{15}) and another peak or null occurs at frequency $f_{19.5}$ (the average of f_{15} and f_{24}). It can be determined that frequency $f_{12.5}$ corresponds to a null 404a because the envelope signal 128a is decreasing at f_{10} but increasing at f_{15}. Similarly, it can be determined that $f_{19.5}$ corresponds to a peak (406a) because the envelope signal 128a is decreasing at f_{15} but increasing at f_{24}. Null 404b and peak 406b in Figure 5b may be similarly detected, where 502b represents the target voltage and 504b, 506b, and 508b represent points along envelope signal 128b having the target voltage 502b. Optionally, at step 308, the process of Figure 3 may detect two successive peaks or nulls, and the frequency in the below equations (used at step 310 to calculate actual length or propagation delay) may be the difference between the frequencies at the successive peaks or nulls.

[0033] Returning again to Figure 3, once a peak or null is detected at step 308, the process of Figure 3 calculates at step 310 the actual length of the transmission line 112. Alternatively or in addition, the propagation delay of a signal through the transmission line may be calculated. Manipulating the equations discussed above, the actual length of the transmission line 112 may be calculated as follows:

for quarter wavelength: $L_{act} = c \div (4 * f_x * \sqrt{e_r})$

for half wavelength: $L_{act} = c \div (2 * f_x * \sqrt{e_r})$

where:

- * indicates multiplication
- f_x is frequency of the signal driven onto the transmission line 112 that resulted in a peak or null being detected at step 308
- L_{act} is the actual length of the transmission line 112
- $\sqrt{e_r}$ is the square root of the relative permeability ("e_r") of the dielectric material (not shown) between the signal line 120 and the return line 114 of the transmission line 112
- c is the speed of light through free space (which is approximately 3 x 10^8 meters/second).

Similarly, the propagation delay of a signal through the transmission line 112 may be calculated as follows:

for quarter wavelength: $D = 1 \div (4 * f_x)$

for half wavelength: $D = 1 \div (2 * f_x)$

where:

- * indicates multiplication
- D is the propagation delay
- f_x is frequency of the signal driven onto the transmission line 112 that resulted in a peak or null being detected at step 308.

Example: Referring again to the example described above in which $\sqrt{e_r}$ is 2 and the initial frequency (f_o) was calculated based on estimated length (L_{est}) of the transmission line of 15 centimeters (f_o = 250 megahertz for a quarter wave signal or 500 megahertz for a half wave signal), the actual length L_{act} of the transmission line 112 and the propagation delay D through the transmission line would be calculated as follows:

- For a quarter wave length signal (f_o = 250 megahertz as calculated above), and assuming that the frequency of the drive signal at which a null or peak was detected at step 308 f_n is 255 megahertz:
 - $L_{act} = 3x10^8 \div (4 * 255x10^6 * 2)$, which is approximately 14.7 centimeters.
 - $D = 1 \div (4 * 255x10^6)$, which is approximately 0.98 nanoseconds.
- For a half wave length signal (f_o = 500 megahertz as calculated above), and assuming that the frequency corresponding to the null or peak detected at step 308 f_n is 510 megahertz:

- $L_{act} = 3x10^8 \div (2 * 510x10^6 * 2)$, which is approximately 14.7 centimeters.
- $D = 1 \div (2 * 510x10^6)$, which is approximately 0.98 nanoseconds.

[0034] Figure 6 illustrates a system that may be generally similar to the system shown in Figure 1. Figure 6, however, includes a digital analyzer 602 for receiving the output 128 of the envelope detector 122 and automatically determining the length "L" of the transmission line and/or the propagation delay through the transmission line. Figure 7 illustrates a simplified block diagram of an exemplary implementation of the analyzer 602, and Figure 8 illustrates exemplary operation of the processor 710 of Figure 7.

[0035] Elements in Figure 6 that are numbered the same as elements in Figure 1 may be generally the same as described above with respect to Figure 1. Analyzer 602 receives input 128 from the envelope detector 122. Analyzer 602 also includes input 608 through which a user or other equipment may enter data. Analyzer 602 also includes two outputs: output 604 for controlling the signal generator 102, and output 606 for outputting results, which may be in the form of control signals.

[0036] As mentioned above, Figure 7 illustrates a simplified block diagram of an exemplary implementation of the analyzer 602. As shown, Figure 7 includes an analog-to-digital converter 702, a digital memory 706, and a processor 710. Note that, if the envelope wave output 128 by envelope detector 122 is already in digital format (e.g., the envelope wave 128b in Figure 4b and Figure 5b), analog-to-digital converter may not be needed. Memory 706 may be any type of digital memory, including silicon based memories, magnetic based memories, optical based memories, etc. Processor 710 is preferably a microprocessor that operates under control of software (e.g., software, firmware, microcode, etc.) that resides in memory 614. Alternatively, processor may consist in part or in whole of hardwired logic circuits.

[0037] Turning now to Figure 8, exemplary operation of the processor 710 of Figure 7 will now be discussed. As mentioned above, the process of Figure 8 may be implemented in software, which is run on processor 710, the process may be hardwired into processor 710, or the process may be implemented in a combination of software and hardwiring.

[0038] As shown in Figure 8, at step 802, the processor 710 receives via input 608 data describing the set-up of transmission line 112 and optionally including a variety of possible parameters, all of which may be stored in memory 706. For example, the processor 710 may

receive data indicating whether the distal end 118 of the transmission line 112 is open or shorted. Similarly, the processor 710 may receive data indicating whether the signals driven onto transmission line 112 are to be based on a quarter wave or a half wave of the estimated length "L" of transmission line 112. Processor 710 may also receive at step 802 an estimated length "L" of the transmission line 112.

[0039] At step 804, the processor 710 calculates an initial frequency setting for the signal generator 102; at step 806, the processor outputs control signal 604 to the signal generator 102, which causes signal generator 102 to generate and output 104 a periodic signal having the initial frequency set at step 804 and then sweep the frequency of that signal through a range or ranges of frequencies. At step 808, the processor 710 detects a peak or a null (or multiple peaks or multiple nulls) in the digitized envelope signal stored in memory 706. At step 810, the processor 710 calculates the actual length of the transmission line 112 and/or the propagation delay through the transmission line. Steps 804, 806, 808, and 810 may be performed in the same general manner as corresponding steps 304, 306, 308, and 310 in Figure 3 and as described above. In Figure 8, however, the processor 710 is programmed to perform these steps automatically (e.g., programmed in software or by hardwired logic). In Figure 3, the steps may be performed manually or automatically or by a combination of manually and automatically performed actions. At step 812, processor 710 outputs via output 606 the results of its calculation or calculations. For example, processor 710 may output at step 812 the actual length of the transmission line 112 or the propagation delay through the transmission line as calculated at sep 810. This output 606 at step 812 may be in a visual format for a human user. Alternatively or in addition, the output 606 at step 812 may be in the form of control signals for controlling another piece of equipment. For example, output 606 generated at step 812 may be used to set a variable delay (not shown in Figure 6) in transmission line 112. As yet another alternative, output 606 produced at step 812 may be output to an electronic storage device.

[0040] Figure 9 illustrates a simplified block diagram of an exemplary test system 900 for testing electronic devices, such as semiconductor devices. For example, the test system 900 of Figure 9 may test the dies of an unsingulated wafer, singulated dies (packaged or unpackaged), or multi-chip modules. Such a system 900 may be configured to test other types of electronic devices, such as printed circuit boards, as well.

[0041] Multiple communications channels (not shown) connect the tester 902 to the terminals of the electronic device 912 being tested (hereinafter the "device under test" or "DUT"). As shown, the DUT 912 may be supported by a moveable stage 914 and housed in a housing 906. The tester 902 generates test data, which is driven through the communications channels (not shown), to the terminals of the DUT 912. Response data generated by the DUT 912 travels in the reverse direction through such communications channels (not shown) back to the tester 902.

[0042] Each communications channel may, and typical does, comprise multiple media. For example, a communications channel may comprise a coaxial cable 904 from the tester 902 to a probe head 907, switches (not shown) and pin electronics (not shown) in the probe head 907, electrical connections (not shown) from the probe head 907 to a probe card 908, strip lines (not shown) and vias (not shown) through the probe card 908 to a probe 910 of the probe card, and a probe 910. Probes 910 make contact with terminals of the DUT 912, and thus probes 910 are the distal end of the communications channels.

[0043] Testing a DUT 912 may involve writing a plurality of test data to the DUT in parallel, and depending on the type of testing, it may be important that the parallel data arrive simultaneously (e.g., within a specified tolerance) at the DUT. Thus, calibrating each of the communications channels to have the same propagation delay (within a specified tolerance) may be important. Because the communications channels from the tester 902 to the DUT 912 are, in essence, transmission lines, the above described exemplary techniques (e.g., Figures 3 and 8) may be used in a test system 900 to measure and then deskew the propagation delays through the communications channels.

[0044] Figure 10 illustrates a simplified block diagram of a portion of a test system, which may be similar to the test system 900 shown in Figure 9, configured to automatically deskew communications channels. Three communications channels 1060a, 1060b, and 1060c—each depicted as a coaxial cable 904a, 904b, and 904c and a probe 910a, 910b, or 910c—are shown in Figure 10. Of course, more or less than three communications channels may be involved. Per the discuss above regarding communications channels comprising multiple media, each communications channel 1060a, 1060b, and 1060c may include additional media. For example, using the example above, a communications channel (e.g., 1060a) may further include switches (not shown) and pin electronics (not shown) in a probe head 907 and strip lines (not shown) and vias (not shown) through a probe card 908. Note that communications channels 1060a, 1060b,

and 1060c in Figure 10 include probes 910a, 910b, and 910c, which are the distal ends of the communications channels.

[0045] As shown in Figure 10, an analyzer 1050a, 1050b, and 1050c is associated with each of the communications channels 1060a, 1060b, and 1060c. Each analyzer 1050a, 1050b, and 1050c may be similar to a combination of the envelope detector 122 and analyzer 602 shown in Figure 6, and each analyzer 1050a, 1050b, and 1050c may execute a process similar to the process shown in Figure 8 to calculate the propagation delay through its associated channel 1060a, 1060b, and 1060c. (Each analyzer 1050a, 1050b, and 1050c may communicate with signal generator 1002 via bus 1070.) Each analyzer 1050a, 1050b, and 1050c may communicate the calculated propagation delay of its associated communications channel 1060a, 1060b, or 1060c to an automatic calibration module 1022 (again communicating through bus 1070). Automatic calibration module 1022 may then set a variable delay module 1030a, 1030b, and 1030c in each channel 1060a, 1060b, and 1060c so that the overall propagation delay through each of the channels 1060a, 1060b, and 1060c is the same or within a specified tolerance. Variable delay modules 1030a, 1030b, and 1030c may be implemented in any suitable fashion. For example, these modules may be implemented as described in U.S. patent application serial no. 10/006,178, filed by Miller on December 4, 2001, and entitled "Adjustable Delay Transmission Line," which is incorporated by reference herein in its entirety. As another example, these modules may be implemented by delaying input of a signal to a driver 1006a, 1006b, or 1006c. As another example, the tester 902 may maintain offset tables for varying starting a test signal on a particular channel in order to compensate for variations in the propagation delays through the channels.

[0046] The signal generator 1002, automatic calibration module 1022, drivers 1006a, 1006b, and 1006c, analyzers 1050a, 1050b, and 1050c, and variable delay modules 1030a, 1030b, and 1030c may be disposed in a tester 902 or may constitute separate equipment. In addition, at least some of the functionality of the analyzers 1050a, 1050b, and 1050c may be moved to the automatic calibration module 1022 or to other equipment. Figure 11 illustrates exemplary operation of the automatic calibration module 1022 of Figure 10 in which much of the functionality of the analyzers 1050a, 1050b, and 1050c is performed by the automatic calibration module 1022. In Figure 11, the automatic calibration module 1022 controls overall calibration of communications channels 1060a, 1060b, and 1060c.

[0047] As shown in Figure 11, at step 1102, automatic calibration module 1022 receives input data (e.g., from an operator) describing the set-up of communications channels 1060a, 1060b, and 1060c. This step may be generally similar to step 802 in Figure 8, except that information is input for each of the communications channels 1060a, 1060b, and 1060c (each treated like transmission line 112 of Figure 6). For example, the automatic calibration module 1022 may receive data indicating whether the distal ends (represented by probes 910a, 910b, and 910c) of the communications channels 1060a, 1060b, and 1060c are open or shorted. (For example, a channel 1060a, 1060b, or 1060c may be left open by not connecting its probe 910a, 910b, or 910c to a conductor, or a channel may be shorted by connecting its probe to ground.) The automatic calibration module 1022 may also receive at step 1102 data indicating whether the calibration signals to be driven onto communications channels 1060a, 1060b, and 1060c are to be based on a quarter wave or a half wave of the estimated length "L" of one of the communications channels 1060a, 1060b, and 1060c. The automatic calibration module 1022 may also receive at step 1102 an estimated length "L" of one of the communications channels 1060a, 1060b, and 1060c.

[0048] At step 1104, the automatic calibration module 1022 calculates an initial frequency setting for the signal generator 1002; at step 1106, the automatic calibration module 1022 causes signal generator 1002 to generate a periodic calibration signal having the initial frequency set at step 1104 and then sweep the frequency of that signal through a range or ranges of frequencies. The automatic calibration module 1022 communicates with the signal generator 1002 through bus 1070, and the periodic signal generated by signal generator 1002 is input through bus 1070 to each of drivers 1006a, 1006b, and 1006c. Steps 1104 and 1106 may otherwise be generally similar to steps 804 and 806 in Figure 8.

[0049] While the signal generator 1002 is sweeping the calibration signal through a range of frequencies, each analyzer 1050a, 1050b, and 1050c looks for a null or peak (depending on whether its communications channel is open or shorted, and whether the initial frequency of the calibration signal was based on a quarter wave or a half wave of the estimated length of the communications channel (see table II above)). Each analyzer may do so generally as shown and described above with respect to step 808 of Figure 8. Each analyzer 1050a, 1050b, and 1050c sends data regarding detection of a null or peak to automatic calibration module 1022 via bus 1070. For example, each analyzer 1050a, 1050b, and 1050c may send to the automatic

calibration module 1022 the frequency of the calibration signal that resulted in detection of the peak or the null.

[0050] At step 1108, the automatic calibration module 1022 receives the digital data from each of analyzers 1050a, 1050b, and 1050c regarding detection of a null of peak. At step 1110, the automatic calibration module calculates the propagation delay through each of the communications channels 1060a, 1060b, and 1060c, which may be done in the same general manner as step 810 in Figure 8. At step 1112, the automatic calibration module 1022 sets a variable delay module 1030a, 1030b, and 1030c in each of communications channels 1060a, 1060b, and 1060c so that the overall propagation delay through all of the communications channels is equal to within a specified tolerance. For example, if channel 1060a is determined to have the longest propagation delay, automatic calibration module 1022 may do the following: set to zero the variable delay 1030a for channel 1060a, set the variable delay 1030b for channel 1060b to the difference between the measured delay of channel 1060a minus the measured delay of channel 1060b, and set the variable delay 1030c for channel 1060c to the difference between the measured delay of channel 106a minus the measured delay of channel 1060c. Automatic calibration module 1022 communicates with the variable delay modules 1030a, 1030b, and 1030c through bus 1070. Of course, the overall delay through the communications channels 1060a, 1060b, and 1060c need not be set such that all are equal. For example, the overall delays may be set so that there is a predetermined difference between the delays through the channels.

[0051] The automatic calibration module 1022 may comprise a processor operating under software (e.g., software, firmware, microcode, etc.) control and a memory for storing the software. The process of Figure 11 may thus be implemented in software operating on a processor. Alternatively, the automatic calibration module 1022 may be hardwired to perform the process of Figure 11, or the automatic calibration module 1022 may comprise both hardwired logic and a processor operating under software control.

[0052] The following illustrates an example showing operation of the process of Figure 11:

- At step 1102, the following parameters are received:
 - $\sqrt{e_r}$ is 2
 - estimated length (L_{est}) of each communications channel 1060a, 1060b, and 1060c is 15 centimeters

 - each communications channel 1060a, 1060b, and 1060c is terminated in an open condition
 - the process of Figure 11 is to be conducted based on a quarter wave drive signal
- At step 1104, the initial frequency is calculated to be $f_o = 3x10^8 \div (4 * 0.15 * 2)$, which equals 250 megahertz.
- At step 1106, the frequency is swept through the range 250 megahertz to 260 megahertz.
- At step 1108, data indicating that a null was detected at a frequency (f_{xa}) of 253 megahertz on communications channel 1060a, at a frequency (f_{xb}) of 255 megahertz on communications channel 1060b, and at a frequency (f_{xc}) of 258 megahertz on communications channel 1060c.
- At step 1110, propagation delays (D) are calculated as follows for each of communications channel 1060a, 1060b, and 1060c as follows:
 - for communications channel 1060a, $D_a = 1 \div (4 * 253x10^6)$, which is approximately 0.988 nanoseconds.
 - for communications channel 1060b, $D_b = 1 \div (4 * 255x10^6)$, which is approximately 0.980 nanoseconds.
 - for communications channel 1060c, $D_c = 1 \div (4 * 258x10^6)$, which is approximately 0.970 nanoseconds.
- At step 1112, the overall delay through communications channels 1060a, 1060b, and 1060c are equalized by setting the variable delays 1030a, 1030b, and 1030c as follows:
 - variable delay 1030a set to zero.
 - variable delay 1030b set to 0.008 nanoseconds.
 - variable delay 1030c set to 0.018 nanoseconds.

[0053] As mentioned above, the distal ends (i.e., probes 910a, 910b, and 910c) of communications channels 1060a, 1060b, and 1060c may be terminated in either an open circuit or a short circuit condition. It is also possible to terminate the proximal ends 910a, 910b, and 910c (which are shown as probes in Figure 10) of channels 1060a, 1060b, and 1060c by bringing them into contact with a DUT or other element with an impedance that is neither an open circuit nor a short circuit. (The proximal end 118 of transmission line 112 in Figure 1 or 6 may be similarly terminated.) In such a case, the channel (or transmission line) would not be terminated

in an open or a short but would be terminated in a known or unknown impedance. If the impedance is known, the fraction of a wavelength of a driving signal that that will cause a peak or null in a standing wave to occur at the proximal end of the transmission line can be calculated using a Smith chart. Any of the above described techniques may then be used to determine the length or propagation delay through the transmission line, except that the calculated-wavelength fraction would be used in place of ¼ wave or ½ wave.

[0054] In fact, techniques such as those described above may be used to determine the value of an unknown impedance that terminates a transmission line (e.g., 112) or communications channel (e.g., 1060a). Figure 12 illustrates an exemplary process for determining the value of an unknown impedance that terminates communications channel 1060a. At step 1202, the distal end 910a of communications channel 1060a is terminated in a known impedance (e.g., an open or a shorted condition) and the frequency of a drive signal that causes a null or peak to be detected at the proximal end 1010a of the communications channel is determined. This may be accomplished using steps similar to 302, 304, 306, and 308 in Figure 3; steps 802, 804, 806, and 808 in Figure 8; or steps 1102, 1104, 1106, and 1108 in Figure 11. At step 1204, the distal end 910a of the communications channel 1060a is terminated in the unknown impedance and the frequency of a drive signal that causes a null or peak to be detected at the proximal end 1010a of the communications channel is again determined, which may be done in the same manner as in step 1202. At step 1206, the value of the unknown impedance is calculated. Knowing the frequency that caused a null or peak while the channel 1060a was terminated in a known impedance (e.g., an open or shorted condition) and the frequency that caused the null or peak while the channel was terminated with the unknown impedance, one can calculate the value of the unknown impedance. As one example, one may use known transmission line equations to calculate the unknown impedance. As another example, one may use a Smith chart to calculate the unknown impedance. (Use of a Smith chart, which shows curves of constant resistance and constant reactance representing load impedance at the end of a transmission line, is well known and fully explained in many reference sources. For example, Smith charts are explained in Hayt, "Engineering Electromagnetics," (McGraw-Hill, Inc. 1981), pp. 444-452, which is incorporated herein in its entirety by reference.) For example, the Smith chart may be used as follows: determine the shift in wavelength from the frequency that caused the null or peak while the communications channel was terminated in the known impedance (e.g., open or short) to the

frequency that caused the null or peak with the channel terminated in the unknown impedance; determine a location on Smith chart that corresponds to the known impedance condition, and move from that location around the Smith chart by the amount of the wavelength shift; determine the real component of the unknown impedance from the voltage standing wave ratio that corresponds to the new location on the Smith chart; and determine the imaginary (reactive) component of the unknown impedance from the angle of the wavelength shift on the Smith chart.

[0055] It is also possible to deskew multiple transmission lines (e.g., communications channels 1060a, 1060b, and 1060c in Figure 10) all of which are terminated in an unknown though equal impedance. Using the techniques described above, one would measure on each transmission line the frequency at which an estimated quarter wave or half wave signal causes a null or peak to appear at the proximal end of the transmission line. One could then deskew the transmission lines one with another using the differences between the measured quarter wave or half wave frequencies on each transmission line.

[0056] It should be noted that, although the input 126 of the envelope detector 122 of Figures 1 and 6 is described as detecting a voltage at the proximal end 110 of the transmission line 112, input 126 could be configured to detect the current through the proximal end 110 of the transmission line 112. For example, a resistance could be disposed between the output 108 of the driver 106 and the proximal end 110 of the transmission line 112 such that the resistance is in series with the output 108 of the driver 106 and the transmission line 112. One input terminal of a differential amplifier could then be connected to the output 108 of the driver 106, and the input terminal of the differential amplifier connected to the proximal end 110 of the transmission line 112. (The inputs of the differential amplifier may be AC coupled (e.g., with capacitors) to the output 108 of the driver 106 and the proximal end 110 of the transmission line 112.) The differential amplifier would thus be configured to amplify the difference between the voltage on one side of the resistance and the voltage on the other side of the resistance. As is known, the voltage drop across a resistance is directly proportional to the current through the resistance. The output of the differential amplifier could then be connected to the envelope detector 122 in the system of either Figure 1 or Figure 6 and the systems of Figure 1 or Figure 6 operated as described above. Figures 2, 4a, 4b, 5a, and 5b would show current rather than voltage.

[0057] Although exemplary embodiments and applications of the invention have been described herein, there is no intention that the invention be limited to these exemplary

embodiments and applications or to the manner in which the exemplary embodiments and applications operate or are described herein.